Comparison between frequency-matched and true sine wave grid-connected photovoltaic modules

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Abstract: - Over the last decade, task forces on photovoltaic systems have delineated international recommendations for adequate interconnection to the electricity supply. Harmonic distortion in the current injection is one of the most relevant points included in these standards. Although several studies have focused on the impact of harmonics on the network, ranging from parallel resonance to inefficient power consumption, none of the previous works have highlighted the difference between generating a true sine wave and a waveform with the same frequency contents as the grid voltage. In the present study it is shown that frequency-matched injection generates less power losses in the transmitting cables and has lesser harmonic impact on the current drawn from the mains by voltage-dependent loads than its counterpart the true sine wave injection. Notwithstanding this, simulation results show that high penetration of true sine wave photovoltaic ac modules enhances the harmonic composition of the voltage and consequently improve the quality of the current drawn by voltage-dependent loads.

Key-Words: - Distributed generation, Harmonics, Inverters, Photovoltaic power generation, Renewable energy.

1 Introduction

Photovoltaic (PV) power generation is becoming increasingly attractive for conforming to renewable energy targets. Setting the example are countries like Germany and Japan with annual installations in the range of 300MW [1]. This remarkable feat is in part due to government incentives but also due to the maturation of the PV industry and the development of interconnection standards. Inverter manufactures, for instance, comply with IEC recommendation 61727 which is, in many cases, adopted by individual countries [2]. Other recognised standards are IEEE 929 for photovoltaic generators and IEEE 1547 for distributed generators [3], [4]. One of the topics discussed in these standards is the harmonic composition of the current injection, which is the essence of the study presented here.

Concerns for current harmonic distortion from static converters for grid-tied photovoltaic generators have been raised since early installations [5]. More recently, studies show that harmonic injection causes parallel resonance with adjacent photovoltaic inverters that, in turn, produces tripping [6]. The latter study concludes that it is better to generate current with a pure sinusoidal waveform. Another contemporary research analyses the interaction between inverters and the generation of harmonics mainly due to control techniques [7].

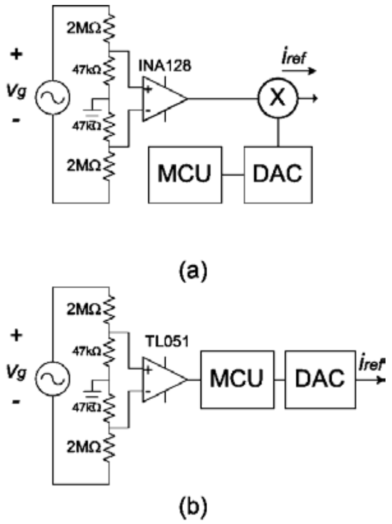
The analysis presented in this paper offers a rather different view as it compares the features of frequency-matched injection to true sine wave injection. This is an issue that has not been addressed properly by previous studies and therefore the goal of the present research is to elucidate the advantages of one method over the other. Inverters with true sine wave injection have an embedded sine wave generator used to control the current. Instead, frequency-matched injection extracts the sinusoidal template from the grid voltage and the inverter generates a current with the same frequency contents. The merits and drawbacks of these forms of current injection are analysed in the following sections as explained next.

First, possible electronic circuits are presented that implement both ways of generating the current injection template. A power conditioning unit (PCU) that utilises such templates has been designed and implemented to perform the tests for controlling the current injection. It is then shown that the power losses in the distribution wires incurred by using a true sinusoidal template are slightly higher than using frequency-matching. Twelve tests have been carried out to assess the impact of harmonic inclusion in the current. These tests involve the connection of inductive, resistive, and switching loads close to the PV generator as occurs in residential installations. Harmonic flows are analysed at the inverter end and at the point of common coupling with the distribution network. Finally, the impact of high penetration of PV ac modules on voltage distortion is studied.

2 Current template generation

2.1 Frequency matched template

A simple way to obtain a sinusoidal template is to extract it from the grid voltage. This is achieved using an instrumentation operational amplifier, INA128, and a voltage divider as shown in Fig. 1 (a). The magnitude of the current reference is set by a microcontroller unit (MCU), ATmega8535, via a digital to analogue converter (DAC), AD5337. The constant magnitude and the sinusoidal (frequency-matched) template are multiplied using an analogue multiplier integrated circuit (IC), AD633. In this case the current reference will contain all the harmonic contents of the voltage plus some distortion introduced by the ICs.



(a)

(b)

Fig. 1. Sine wave generation circuits: (a) Frequency-matched template; (b) true sinusoidal template.

2.2 True sinusoidal template

This form of sine wave generation uses a digital look-up table stored in memory inside the MCU and a DAC as illustrated in Fig. 1 (b). The address of the memory location is specified by an internal free-running counter that is synchronized to the grid voltage using an op-amp as comparator, TL051. The amplitude of the template is set by multiplying the contents of the memory location by a constant number using the internal arithmetic logic unit of the MCU. Clearly, the harmonic distortion of the template strongly depends on the resolution of the DAC and the clock rate of the counter. The DAC input is updated at 80kHz and has a resolution of 16 bits.

3 Power conditioning unit

Fig. 2 shows the power converter used for the tests.

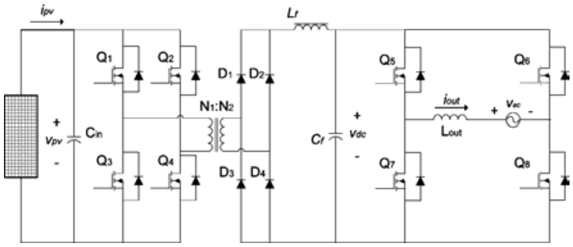


Fig. 2. Power conditioning unit for photovoltaic ac module

The PV ac module converter comprises two stages: voltage amplification and grid coupling. The first stage is attained using a full-bridge inverter connected to a high-frequency transformer and a full-bridge rectifier. The output is filtered through L_f and C_f. The dc-link voltage, v_{dc}, is controlled at 400V by varying the duty cycle of transistors Q_1 to Q_4. The second stage is a voltage-source-inverter (VSI) that uses current-mode-control to shape the current injection into the mains. During the positive half-cycle of the grid voltage transistors Q_5 and Q_8 are turned on to force the current to increase. When these transistors are turned off the current will free-wheel through the reverse diodes of Q_6 and Q_7 and therefore decrease. During the negative half-cycle of the grid voltage transistors Q_6 and Q_7 are turned on to force the current to decrease. Turning them off forces the current to flow through the body diodes of Q_5 and Q_8 and therefore the current increases.

4 Power injection and power losses

4.1 Frequency matched power injection

Neglecting sub-synchronous and inter-harmonics, the instantaneous voltage at the inverter end can be expressed as a summation of sinusoidal components using Fourier series for periodic signals as,

$$\hat{v}(t)=\sum_{n=1}^{\infty}\hat{v}_n\sin\left(2\pi 50nt+\delta_n\right). \qquad (1)$$

Using phasor representation, (1) can be expressed as,

$$\hat{V} = \sum_{n=1}^{\infty} \hat{V}_n e^{j\delta_n} , \tag{2}$$

where the modulus is in RMS without loss of generality. Evidently, the terms cannot be added in this last equation because they represent components at different frequencies. Knowing that harmonics are a percentage of the fundamental, $\hat{V}_1$, (2) can be rewritten as,

$$\hat{V} = \hat{V}_1 \sum_{n=1}^{\infty} \hat{p}_n e^{j\delta_n} , \tag{3}$$

where $\hat{p}_n$ is the percentage of the n^{th} harmonic with respect to the fundamental. Since the current injection matches the voltage frequency contents, the current can be expressed as,

$$\hat{I} = \hat{I}_1 \sum_{n=1}^{\infty} \hat{p}_n e^{j\delta_n} . \tag{4}$$

Assuming all current frequency components are in phase with the voltage frequency components, the power injection is defined as,

$$\hat{P} = \hat{V}_1 \hat{I}_1 \sum_{k=1}^{\infty} \hat{p}_k^2 . \tag{5}$$

A proof of the previous result can be found in [8]. Alternatively, the same result can be achieved by working everything in time-domain and using trigonometric identities. The subscript *k* is used instead of *n* to indicate that the components in this case can be added algebraically as they represent real power injection in watts. In other words, $\hat{P}$ is the average of the instantaneous power flow.

4.2 True sinusoidal power injection

In this scheme, the current injection contains only the fundamental, $\tilde{I} = \tilde{I}_1$, and therefore the power injection is $\tilde{P} = \hat{V}_1 \tilde{I}_1$. To inject the same amount of power as (5), the magnitude of the current has to be,

$$\tilde{I}_1 = \hat{I}_1 \sum_{k=1}^{\infty} \hat{p}_k^2 . \tag{6}$$

4.3 Power losses in cabling

PV ac modules have the advantage that can be connected to the closest mains outlet to the roof. This outlet is at a given distance from the point of common coupling with the distribution network and is normally wired using 13A cable. Letting the impedance of the cable be Z = R + *j*X, the real power losses for the frequency-matched inverter are,

$$\hat{P}_{loss} = R\hat{I}_1^2 \sum_{k=1}^{\infty} \hat{p}_k^2 . \tag{7}$$

In contrast, power losses with a current defined by (6) are,

$$\tilde{P}_{loss} = R\hat{I}_1^2 \left(\sum_{k=1}^{\infty} \hat{p}_k^2 \right)^2 . \tag{8}$$

Because $\hat{p}_1 = 1$, $\sum \hat{p}_k > 1$, and therefore $\left(\sum \hat{p}_k^2 \right)^2 > \sum \hat{p}_k^2$. Therefore, power losses in the transmitting cable are higher when using true sine wave inverters.

5 Load tests

A photovoltaic ac module producing an output of 70W is connected to the closest electricity outlet. The cable length from this outlet to the point of common coupling with the grid (at the power meter) is 30 meters and has an impedance of Z = 0.7 + *j*1.2Ω at 50Hz. The grid voltage at the meter end has the waveform shown in Fig. 3 and has the harmonic contents shown in Table 1 (only odd harmonics up to the 15th are listed).

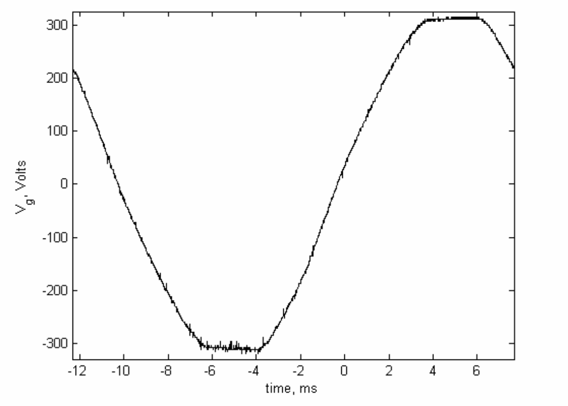


Fig. 3. Grid voltage

The first row contains the RMS value of the n^{th} harmonic and the second row contains the percentage of the n^{th} harmonic with respect to the fundamental.

Table 1. Grid voltage harmonics

	RMS	%		RMS	%
1st	232.3	100.0	9th	1.39	0.6
3rd	7.74	3.3	11th	0.40	0.2
5th	4.36	1.9	13th	0.51	0.2
7th	2.54	1.1	15th	0.48	0.2

The total harmonic distortion of the voltage is 4%. Table 2 provides the percentage of permissible harmonic contents with respect to the fundamental as specified in recommendation IEC 61727 and the British standard G83 for current injection into the grid from photovoltaic generators [9].

Table 2. Recommended harmonic distortion in current injection

	IEC 61727	G83		IEC 61727	G83
3rd	4	2.3	11th	2	0.33
5th	4	1.14	13th	2	0.21
7th	4	0.77	15th	2	0.15
9th	4	0.4			

Clearly the G83 recommendation is more conservative and would rule out the use of frequency-matched inverters because the grid voltage is more polluted than the requirement. Moreover, recommendation IEC 61727 explicitly suggests that harmonic content in the current should be exclusive of harmonic content in voltage. In other words, if the 3rd harmonic of the voltage is 3.3%, then it is possible to subtract the same percentage to the current injected using frequency-matching in order to satisfy the standard.

The current waveforms and harmonic contents of the frequency-matched inverter and the true sine wave inverter are shown in Fig. 4 and Table 3 and 4 respectively.

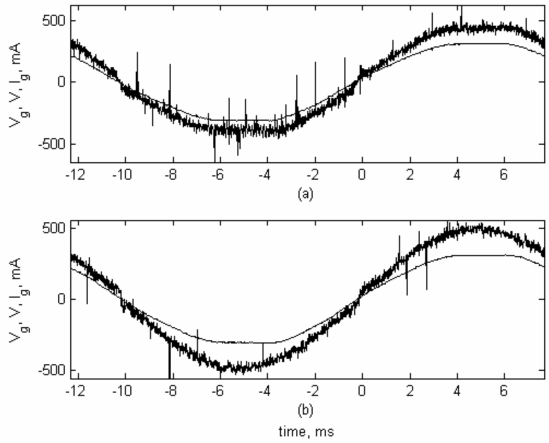


Fig. 4. (a) Frequency-matched grid current and voltage, (b) true sine wave grid current and voltage

Table 3. Frequency-matched grid current harmonics

	RMS	%		RMS	%
1st	315.5	100.0	9th	2.5	0.8
3rd	15.9	5.0	11th	0.9	0.3
5th	5	1.6	13th	0.25	0.8
7th	7.3	2.3	15th	0.29	0.9

Table 4. True sine-wave grid current harmonics (mA)

	RMS	%		RMS	%
1st	348.4	100.0	9th	3.5	1.0
3rd	2.2	0.6	11th	3.8	1.1
5th	2.7	0.8	13th	2.2	0.6
7th	1.5	0.4	15th	1.6	0.5

The frequency-matched inverter has a total harmonic distortion of 7.1% and the true sine wave inverter has a THD of 3%. If in the former case we subtract the percentage of the harmonics introduced by the grid voltage, then THD would fall to approximately 3% and satisfy the IEC recommendation.

The following tests will further clarify the merits of one scheme of current injection over the other. Twelve tests have been contemplated to emulate a real environment in a solar home. Six of these were done using the frequency-matched inverter and six were done with the true sine wave inverter. Of each set of six tests, two were done with resistive loads, two with inductive loads, and two with switching loads. One of each set of two corresponds to a power demand higher than the PV generation and another to a lower demand. The experiment set-up is shown in Fig. 5.

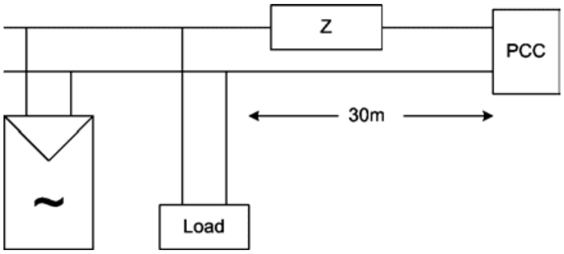


Fig. 5. Load test set-up

5.1 Resistive load tests

A resistor is connected at the inverter end. In one case, the resistor draws 150W and therefore there are 80W drawn from the grid. In a second case, the resistor draws 50W and there are 20W flowing into the grid. Evidently, because the load is resistive, the current drawn will contain all the harmonics present in the voltage. Table 5 summarises the harmonic contents of the current injected or absorbed from the grid.

Table 5. Current harmonics with resistive load

Inverter	Frequency-matched		True sine wave	
Load	50W	150W	50W	150W
3rd	9.6	2.7	3.8	7.8
5th	1.8	2.5	4.8	5.1
7th	4.3	0.4	1.2	1.7
9th	4.4	1.5	3.0	2.2
11th	2.5	1.0	2.4	1.6
13th	3.3	0.8	1.3	1.1
15th	3.7	1.2	1.8	1.3
THD	12.8	4.4	7.6	10.0

It is readily seen that because the resistor demands power at all harmonics, the impact on the resulting grid current is tremendous when using the true sine wave inverter at high power demand (150W). In contrast, at low power demand the frequency-matched inverter seems to introduce more harmonics in the system. This is because the injected current has lower amplitude and harmonic components prevail.

5.2 Inductive load tests

Motors are widely found in households in the form of fans, refrigerators, blenders, pumps, etc. Two motors are used: a) 150W/450Vars, and b) 28W/30Vars. The harmonic distortion of the current drawn by these motors is shown in percentage of the fundamental in Table 6.

Table 6. Motor harmonic content percentage

Motor	(a)	(b)		(a)	(b)
3rd	9.93	9.04	11th	0.39	0.29
5th	3.81	0.57	13th	0.37	0.23
7th	2.67	0.69	15th	0.33	0.06
9th	1.73	0.34			

From the table it is clear that both motors require much power in the third harmonic. Table 7 lists the resulting harmonic composition of the current flowing to or from the grid with the PV ac module connected.

Table 7. Current harmonics with inductive load

Inverter	Frequency-matched		True sine wave	
Load	(a)	(b)	(a)	(b)
3rd	8.4	0.8	9.9	4.5
5th	4.4	2.6	4.3	1.3
7th	2.5	3.2	2.9	1.3
9th	1.8	1.5	1.1	1.1
11th	0.7	1.4	0.5	1.3
13th	0.3	1.3	0.4	0.5
15th	0.1	1.6	0.1	1.0
THD	10.0	5.1	11.2	5.3

The frequency-matched inverter offers a slightly better solution to prevent current harmonics from flowing into the grid. A point to highlight is that since PV ac modules do not provide reactive power, all of it must be extracted from the grid and this affects the power factor at the grid end.

5.3 Switching load tests

Switching power supplies are found in almost all electronic appliances. These contribute the most to the pollution of the electricity grid in a residential environment. A power supply for the test is operated at two power levels: 150W and 50W.

Table 8 shows the harmonic contents in percentage of the current flowing into the mains with the PV ac module connected. It is observed that in all instances the third harmonic is greater than the fundamental. Also, we can infer that both ways of current injection have a similar impact on the grid current when a switching load is present in the circuit.

Table 8. Current harmonics with switching load

Inverter	Frequency-matched		True sine wave	
Load	50W	150W	50W	150W
3rd	109.45	114.99	105.07	143.74
5th	76.94	56.36	70.78	81.07
7th	42.30	10.89	36.27	29.57
9th	26.21	20.21	22.39	11.75
11th	8.00	25.300	8.30	28.49
13th	11.83	14.40	11.38	26.11
15th	13.45	3.64	11.09	9.93

6 High penetration of true sinusoidal photovoltaic ac modules

Previous tests show that it is slightly better to generate a current with the frequency contents of the grid voltage in order to reduce losses in the network and to satisfy the demand of voltage dependent loads. However, good engineering practices dictate that the network should be kept as clean as possible. In fact, it is next shown that the voltage at the load end can be improved by having high penetration of true sinusoidal photovoltaic ac modules.

A system of 10 solar homes with a plant of 20 PV ac modules each has been modelled using EMTP-RV. Residential electricity networks can be closed-loop or radial Fig. 6. For simplicity a radial network with 10 nodes has been considered. Each home is separated by a distribution line with impedance $Z_d = 0.5 + j1\ \Omega$. Each individual PV plant is connected to the distribution network via a cable with a 50Hz impedance of $Z = 0.7+j\ 1.2\ \Omega$ as shown in Fig. 6.

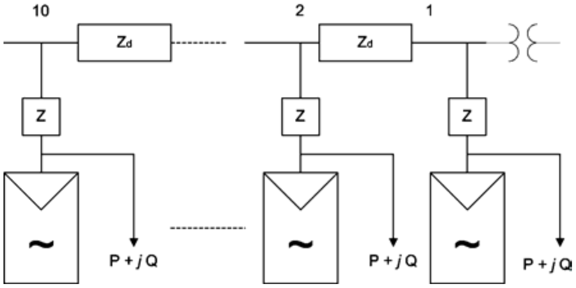


Fig. 6. Radial network of solar homes

One of the houses at the extreme is connected to the grid, for instance, to one phase of the distribution transformer. The grid voltage has harmonics as shown in Table 1. Each home has a load, P + *j*Q, with 0.9 lagging power factor. Two scenarios are contemplated: a) power load, P, lower than the PV generation, P_{pv}, and b) power load higher than the PV generation.

In Table 9 it is seen that voltage total harmonic distortion is lowest for the solar home that is more distant from the transformer for both power load levels.

Table 9. Voltage total harmonic distortion with high penetration of ac modules

Node	$P>P_{pv}$	$P<P_{pv}$	Node	$P>P_{pv}$	$P<P_{pv}$
1	4.03	4.03	6	3.40	3.58
2	3.87	3.91	7	3.33	3.52
3	3.73	3.81	8	3.27	3.49
4	3.60	3.72	9	3.23	3.46
5	3.49	3.64	10	3.21	3.45

7 Conclusion

Grid voltage integrity has been one of the most important concerns since the creation of the first power system several decades ago. With the advent of electronic equipment the quality of voltage supply has widely deteriorated, pushing distortion to its limits. This problem can be further intensified or alleviated with new static generators that have the capability of producing current with any desirable waveform. It has been demonstrated that current waveforms matching the grid voltage result in a more efficient use of power. However, it is also shown that high penetration of true sinusoidal PV ac modules enhances the quality of the voltage supply. So far, the decision to use either approach has been taken by inverter manufactures following international recommendations. Yet, the on-going installations around the world may elicit more pros and cons of harmonic generation by PV sources.

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